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BRIDGING THE GAP BETWEEN INJECTOR HYDRAULICS AND COMBUSTION PHENOMENA IN LIQUID PROPELLANT ROCKET ENGINES

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BRIDGING THE GAP BETWEEN INJECTOR HYDRAULICS AND COMBUSTION PHENOMENA IN LIQUID PROPELLANT ROCKET ENGINES[1]

Jack H. Rupe

ABSTRACT

The non-reactive properties of the sprays produced by a single pair of impinging jets are utilized as the basis for the design of several rocket injectors at the 20,000 pound thrust level. These designs are predicated upon the assumption that the mass distribution and mixture-ratio distribution are the significant parameters insofar as combustion is concerned, and further that these properties may be controlled through proper injector design. The design criteria are presented in some detail, and the results of the performance evaluation of these several injectors are presented.

I. INTRODUCTION

For many years the unpredictable combustion phenomena encountered in liquid propellant rocket engines have been associated with the injection system. Yet the mechanism that controlled these interactions has not been defined. It was therefore the combination of a desire to define such a mechanism and the conviction that the problem could at least in part be resolved with adequate knowledge of the hydrodynamic properties of the injected fluids that led the Jet Propulsion Laboratory into an investigation of the non-reactive

[1]This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratories, California Institute of Technology, under Contract NASw-6, sponsored by the National Aeronautics and Space Administration.

properties of sprays and jets. Although this program purposely divorced itself from combustion problems it was based upon the implicit assumption that its significant results could be applied to a reacting system. These non-reactive studies were based upon the assumption that the really significant injector functions must include the production of controlled, predictable, and presumably stable spray properties in the pre-reaction zone of a combustion chamber. Obviously since the injector itself does not enter into the reaction its geometry is insufficient for correlation with combustion but must first be related to the spray properties that a given geometry will produce. A subsequent correlation is then necessary to correlate spray characteristics and combustion phenomena. It is noted that, conceptually at least, there are an infinite number of injector geometries that can produce a given mass and mixture-ratio distribution, whereas intuition suggests that a given set of combustion properties are uniquely related to a given mass and mixture-ratio distribution.

First efforts to demonstrate the feasability of this latter correlation have been based upon the further assumption that those spray properties produced by a given injector geometry are also achieved by propellants injected with the same configuration into an operating combustion chamber. Although it is reasonable to expect that combustion will effect such sprays to some degree, the fact remains that these effects are simply additional variables and serve only to modify the detailed requirements of the properties produced by the injector. Thus injection into a combustion environment does not alter the requirement that the significant injection parameters must be known quantities that are stable and predictable.

It has already been indicated that of the several spray characteristics that could be studied only mass distribution and mixture-ratio distribution have been considered significant for this first evaluation. Mass distribution (actually axial-mass-flow-rate distribution for a cylindrical chamber with one-dimensional flow) is included since it defines the relative concentrations and presumably, on an absolute scale, should define the maximum tolerable concentrations for any given propellant combination. It provides a basis for achieving uniformity in concentrations and hence axial velocities in a typical chamber. Mixture-ratio distribution is simply a measure of the degree of mixing achieved by the injection processes. Presumably the ideal situation from a chemical viewpoint is attained when a predetermined mixture ratio (i.e., peak performance or its equivalent) is achieved on a molecular scale in a minimum time and/or space. For most applications however it is probable that the required scale of mixing is substantially coarser than molecular. It is noted that the choice of these parameters as the more significant ones was somewhat arbitrary and should not imply that, at least in certain cases, a spray property such as droplet-size distribution might not be even more important.

The overall performance of a rocket motor must of course be related to the properties of the complete injector. However in those instances where the injector is a composite of a number of essentially identical elements then the properties of the element can be used to construct these gross characteristics. In practice it is this latter procedure that is utilized for obtaining a prescribed injection pattern (i.e., mass distribution). In most cases it is simpler to "organize" the mass distribution of a number of small elements to conform to a particular chamber geometry than it is to fabricate suitable chamber boundaries to suit the mass distribution of a small number (i.e., one or two) of elements. Previous experimental evidence also tends to substantiate the idea that appreciable numbers of small elements also assist in achieving the required overall-spray properties.

II. NON-REACTIVE SPRAY STUDIES

The various types of injector elements (i.e., the smallest subdivision from which design combustion processes could be expected) which have been utilized as the basis for injector design have included only a few for which any appreciable amount of hydrodynamic information is available. In particular these include the hollow-cone spray which has been studied extensively for applications in gas-liquid combustors and the unlike-on-unlike impinging-stream spray. This latter element has been studied by Heidman and Humphreys (Ref. 1) of NACA (cf. Ref. 1) and Norman W. Ryan of MIT (cf. Ref. 2) as well as others and was chosen as the basis for a rather extensive study at JPL because of its relative simplicity, its wide applicability to bipropellant rocket systems, and because it promised a means of achieving intimate physical mixing of the two components on the scale required to support combustion in a near minimum time. The results of these studies have been presented from time to time in the bimonthly Laboratory Publications and in particular in Refs. 3 and 4. In addition, at least insofar as the mass-distribution data are concerned, some of the earliest information was reported in Ref. 5. These data will not be unnecessarily repeated here. However in order to provide a basis for interpreting the spray properties which are to be discussed, and in an attempt to give physical significance to the terms mass distribution and mixture-ratio distribution a very brief review of the experimental phases of this work is probably justified.

Figure 1 is a collection of photos which shows first as part (a) an artists concept of the several more basic injector elements. Although there are certain obvious differences it is important to note that the prime objective in every case is to achieve some degree of controlled mixing with a particular distribution, and further, that in every case the element depends upon the hydrodynamic properties of free liquid sheets or jets to accomplish this objective. Thus the control of these properties is prerequisite to the control of mass and mixture-ratio distributions. It should also be noted at this point that once the required properties of an injector spray have been defined, any or all of such elements could be utilized to achieve those requirements. And it is only because the properties of the unlike-on-unlike impinging streams have been evaluated in some detail that this element was chosen as the basis for additional investigation.

Figure 1b shows two views of a spray produced by impingement of a pair of nearly identical water jets. It is noted that the bulk of the spray is concentrated about a "resultant momentum line" and has (at least in this case of identical jets with equal momenta) a nearly

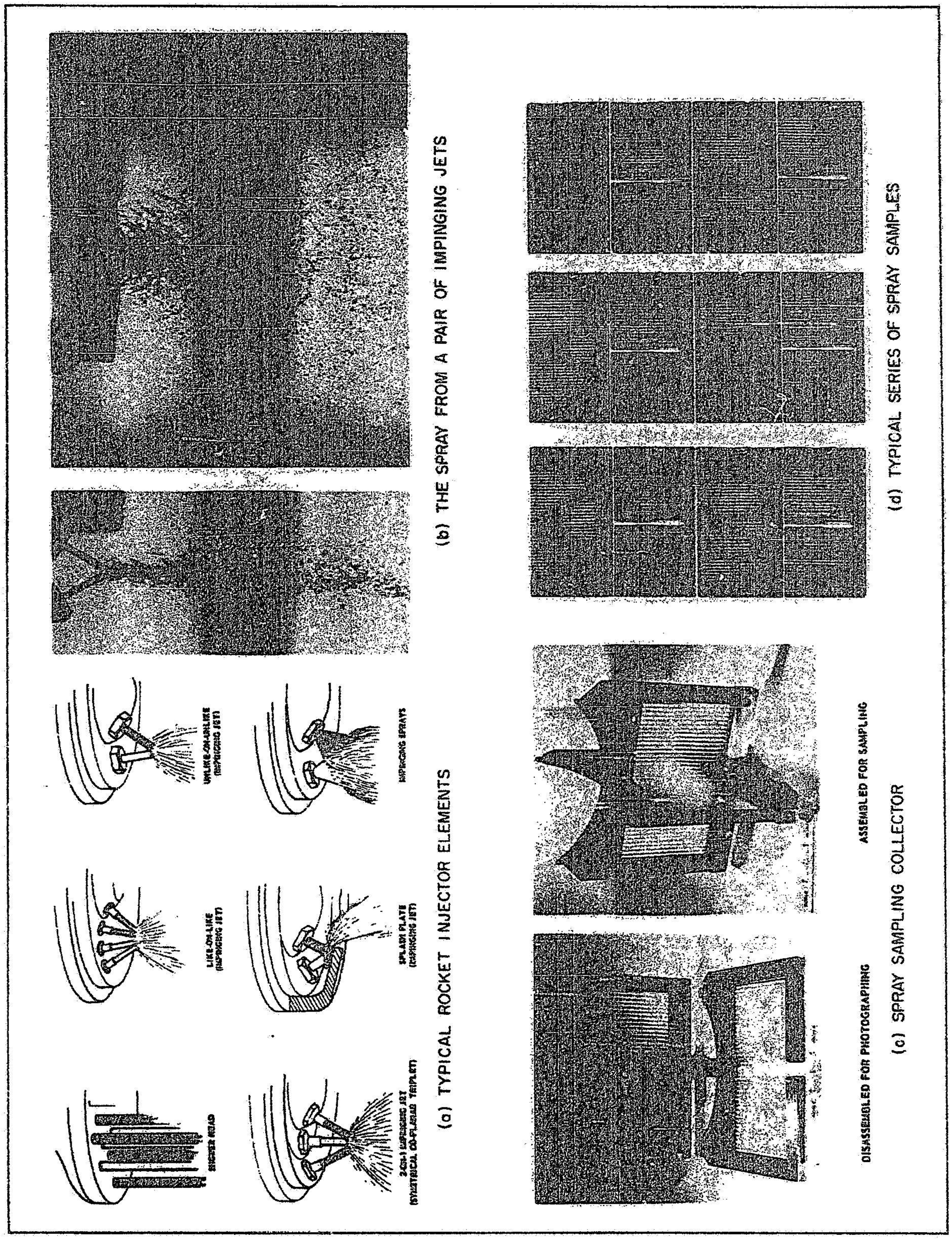


Fig. 1. Montage of Non-Reactive Spray Experiments

elliptical cross section. Now if a collector of the type shown in Fig. 1c is exposed to such a spray for a reasonable time interval, a series of samples such as are shown in Fig. 1d will be obtained. In this case the vertical height of the sample in each tube is proportional to the local mass flow rate at a different position within the spray. In addition, if the injected fluids are immiscible then they will separate after the sample is obtained (as indicated in the photographs) and it is possible to determine the relative flow rates passing the particular point in the spray and hence obtain a local mixture ratio.

A great deal of this kind of information was obtained with the carbon-tetrachloride-water system and has been utilized to produce a correlation of a quantity E_m, known as a "mixing factor", and the gross dynamic properties of the two jets (cf. Ref. 4). This mixing factor is essentially a summation of the mass-weighted value of the ratio between the local mass-fraction ratio and the nominal mass-fraction ratio. It's limits have been adjusted to values of 0 and 100 and can be imagined to represent the percentage of the total spray that has achieved the nominal mixture ratio. In another sense it can be visualized as representing the degree to which the spray has achieved the intended mixture ratio.

Figure 2 shows the correlation resulting from this effort which has been used as the basis for the conclusion that (within the limitations of the experiments) the most uniform mixture ratio distribution is achieved in the spray produced by a pair of impinging streams when the parameter $\left[1/1 + (\delta_1 V_1{}^2 D_1/\delta_2 V_2{}^2 D_2) = 0.5\right]$ or when the quantity ($\delta_1 V_1{}^2 D_1 / \delta_2 V_2{}^2 D_2 = 1$). This latter quantity has become known as the "uniformity criteria".

If in addition to the usual mixture ratio requirements it is also required that the element satisfy the uniformity criteria then for any given propellant system the orifice diameter ratios and the jet velocity ratio are defined by Eqs. (3) and (4) respectively of Fig. 2. If it is further assumed that total flow rate for the element W_T is determined from other considerations, then Eq. (5) must also be satisfied. Obviously then, the arbitrary choice of one velocity or one diameter will determine all other values. In any event Eqs. (3) and (4) are satisfied when the element will produce a spray having a near uniform mixture-ratio distribution. Therefore within the limitations of the assumptions already discussed it is possible to predetermine the injector geometry that is required to produce a near uniform mixture-ratio distribution.

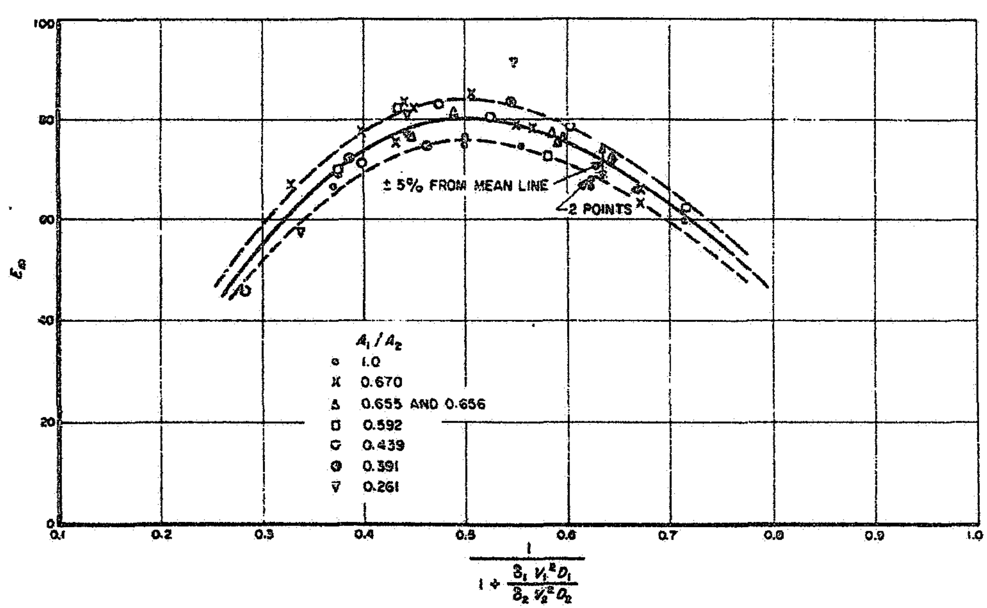


Fig. 2. A Correlation of E_m and $\delta_1 v_1{}^2 D_1 / \delta_2 V_2{}^2 D_2$ and Its Application

For the maximum value of E_m, i.e., near-uniform r distribution

$$\frac{\delta_1 V_1{}^2 D_1}{\delta_2 V_2{}^2 D_2} = 1.0 \text{ (Uniformity Criteria)} \tag{1}$$

$$\frac{\delta_2 V_2 D_2{}^2}{\delta_1 V_1 D_1{}^2} = r \text{ (by Definition)} \tag{2}$$

Combining (1) and (2)

$$D_1/D_2 = \left[\delta_2/\delta_1 \times 1/r^2\right]^{1/3} \tag{3}$$

$$V_1/V_2 = \left[\delta_2/\delta_1 \times r\right]^{1/3} \tag{4}$$

Then for a particular flow rate

$$V_2 D_2{}^2 = 4W_T/\pi(1/r + 1) \tag{5}$$

Unfortunately no simple way of characterizing the mass distribution of the spray produced by an element has been devised. This tends to be particularly difficult since these distributions tend to be strong functions of the geometry and dynamic properties of the jets as well as the included angle between the jet centerlines (i.e., impingement angle). Thus, to date at least, it has been necessary to utilize experimental information, which has been obtained with an actual experimental injector element similar to the proposed design as the basis for a composite design. It should be noted that the geometrical properties of the sprays produced by a pair of jets having similar geometry as well as similar dynamic properties tend to be quite insensitive to scale and absolute levels of mass flow rates. Thus it is possible to approximate the mass distributions of a proposed element from other data that may be available (e.g., from the experimental records of data used to determine the mixing correlation).

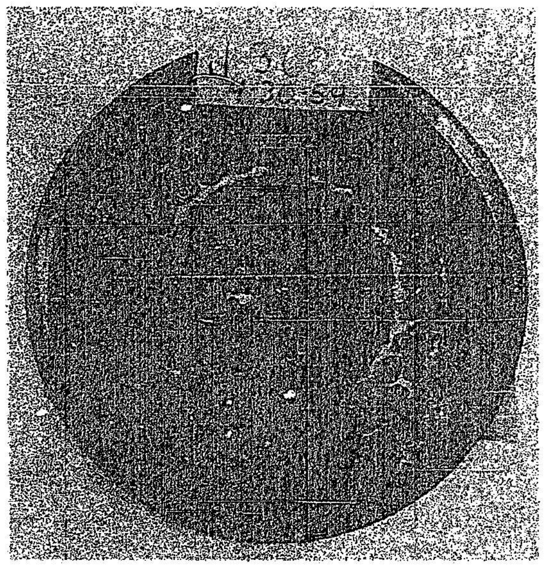
It can now be seen that (again within the limitations of the previously stated assumptions) these data provide a means of obtaining, first, a near uniform mixture-ratio distribution of the injected propellants, and secondly, a means of predicting and controlling the axial-mass-flow-rate distributions in a chamber of arbitrary cross section. However the assumptions upon which the method is based are subject to verification and the relative combustion effects are yet to be evaluated. Therefore the significance of this approach is dependent upon a verification of the applicability of the data obtained with non-reactive fluids to actual combustion systems.

III. RELATING COMBUSTION PHENOMENA AND INJECTION PROPERTIES

The experimental correlation of injector (i.e., combustor) performance with the presumed significant spray properties of mass distribution and mixture-ratio distribution would require the evaluation of very large quantity of experimental hardware due to the interdependence of these properties on gross mixture ratio and injector geometry. Therefore the first test of the hypothesis was restricted to a relatively simple "demonstration" of significance (or lack of same).

In order to minimize the amount of background material that would have to be generated and because an appreciable amount of test hardware was already available it was convenient to base this demonstration upon the so-called "Corporal" propulsion system. The injector for this system consists of 52 pairs of impinging unlike-on-unlike jets arranged as shown in Fig. 3 so as to produce two concentric rows of impingement points which tend to concentrate the injected fluids in an annular section of the combustion chamber. Thus, this injector (or one similar to it) should provide a suitable comparison between a "concentrated" mass distribution and a more uniform distribution. In addition it seemed significant that this system had already undergone a rather extensive development program without realizing its full potential so that if a substantial improvement resulted from the application of the hypothesis it could not be considered as a complete coincidence. It is also true that the liquid phase reactions that are available with this system tend to minimize the importance of droplet size distributions.

Thus it seemed that a significant demonstration could be achieved by comparing the properties of the original Corporal injector with similar designs which were based on the non-reactive data and intended to produce (1) similar but nonuniform mass distributions having uniform mixture-ratio distribution and (2) an injector that was presumed to produce uniform mixture-ratio distribution and uniform mass distribution.



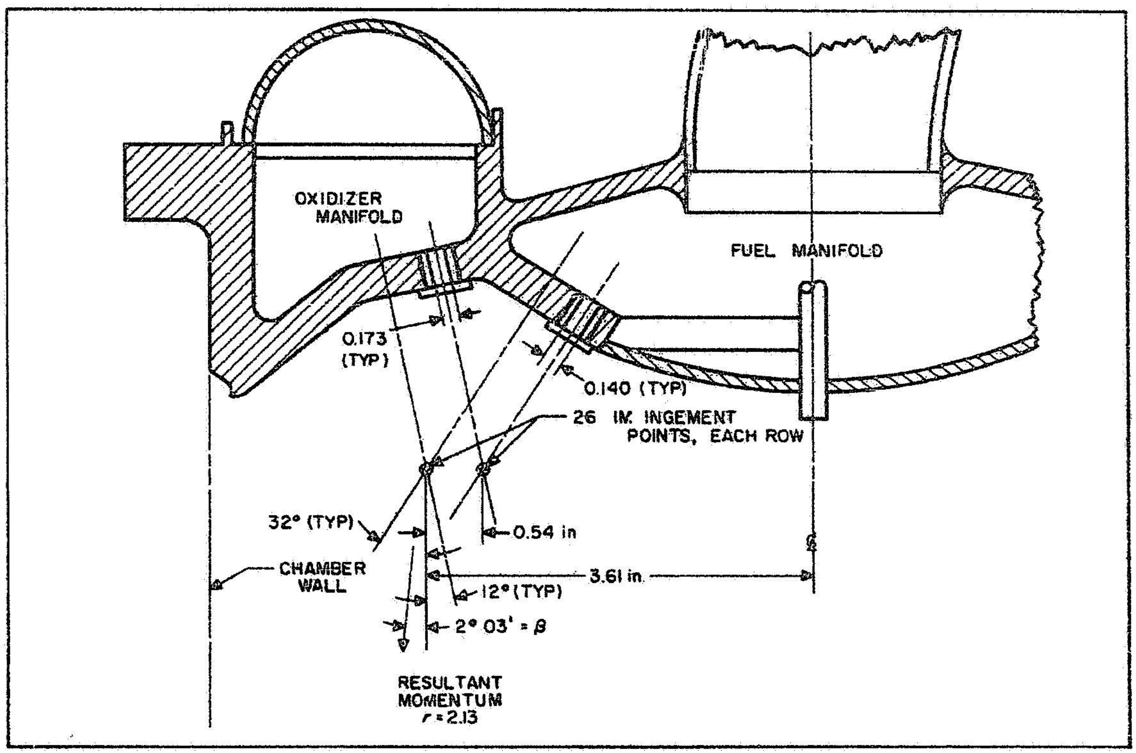


Fig. 3. Corporal Injector (J-360) with Sketch of Orifice Geometry

The only disadvantage to this approach was that the optimum mixture-ratio for the Corporal injector had been set at a value of 2.13 with a resulting performance level that is substantially lower than is possible at the peak performance mixture ratio of 2.80. Thus it was first necessary to obtain a comparison with a uniform mixture-ratio design based on a mixture-ratio of 2.13 and then subsequently with a similar design based on 2.80. Since the changes in jet properties (relative to the Corporal) required to produce these conditions also resulted in some changes in mass distribution, a first attempt to evaluate these latter effects consisted of the evaluation of two additional injectors which retained all of the element properties for the respective injectors but returned the resultant momentum line of each element to the value achieved by the Corporal at r = 2.13. This was accomplished by rotating the jet centerlines about the impingement point. In all other respects the centerline geometry of these four injectors were similar to the Corporal. Thus the several injectors to be included in the demonstration can be summarized as follows:

1. A Corporal injector which historically produces optimum performance at a gross mixture-ratio of 2.13.
2. An injector having Corporal centerline geometry but modified by changing only the fuel orifice diameter so as to produce uniform mixture-ratio distribution at r = 2.13.
3. As in (2) but with the element rotated about its impingement point in order to duplicate the Corporal resultant momentum line for r = 2.13.

4. As in (2) but designed for uniformity at r = 2.80 (i.e., peak performance).
5. As in (3) but designed for uniformity at r = 2.80.
6. An injector having the same number of elements and the same geometry for the element as used in (4) and (5) but with the resultant momentum angle equal to zero and the elements rearranged to produce a near uniform axial-mass-flow-rate distribution.

IV. APPLYING NON-REACTIVE DATA TO INJECTOR DESIGN

The subsequent experimental program consisted essentially of the design, fabrication, hydraulic evaluation, and performance testing of a series of injectors that conformed to the requirements listed in the previous section. For the four Corporal-like injectors the centerline geometry was predetermined and since the propellant system (i.e., propellant densities) and design mixture-ratios were specified, it was a relatively straight forward procedure to complete those designs. In order to retain as much similarity as possible the oxidizer orifice diameter was arbitrarily assigned the same value as used in the Corporal and since the number of elements was unchanged the jet velocity for the oxidizer system was also duplicated. As was already noted the remaining properties of the injector are then determined. The significant design dimensions are summarized in Table 1.

It is extremely important to remember at this point that the significance of orifice diameter in these designs is predicated upon the assumption that the jets are stable, symmetrical, and reproducible

Table 1. Injector Design Specifications

Number of elements = 52

Total thrust level = 20,000 lb

Propellants - Corporal $\left[(\text{Specific Gravity})_f = 1.073;\ (\text{Specific Gravity})_{ox} = 1.550\right]$

Engine constants:

$$f_c/f_t = 2.03$$

$$\epsilon = 4.48$$

$$P_c = 300 \text{ psia}$$

$$P_o = 13.5 \text{ psia}$$

$$C_{F(\text{Expected})} = 1.410\ \lambda\ C_d = 1.362$$

Injector Identification	Design r	Orifice Diameters		β(2)
		Oxidizer	Fuel	
Corporal	2.13(1)	0.173	0.140	2°05'
No. 1	2.13	0.173	0.118	5°40'
No. 2	2.13	0.173	0.118	2°05'
No. 3	2.80	0.173	0.0986	3°42'
No. 4	2.80	0.173	0.0986	2°05'
No. 5	2.80	0.173	0.0986	0°

(1) Actually determined from experimental performance.

(2) β = Angle between resultant momentum line and chamber axis at design r.

(cf. Ref. 3). Therefore the detail orifice designs conformed to the requirements of Ref. 3. The results of incorporating these orifice requirements into a Corporal-like injector are illustrated in Fig. 4 which includes a photograph of one of these Corporal-like injectors and a sketch of the orifice installation as well as the essential manifold components. The hydraulic evaluation of the injector included an experimental check of the hydrodynamic properties of each jet both before and after installation into the injector. For this purpose the jet symmetry and the centerline velocity were evaluated with the flat plate dynamic head probe (cf. Ref. 6) and the flow rate was determined by direct sampling and weighing.

The data obtained in this manner after installation of the orifices in Injector Number 3 are shown in Fig. 5 and are typical of all the Corporal-like injectors. It can be seen that even though a rather extensive development of the manifold had already been completed, the individual flow rates varied by as much as 5% and that the centerline-stagnation-pressure ratio varied by nearly 10% from a mean value and that this value was additionally degraded due to manifold effects. Although it was recognized that these data would not produce an optimum experiment, it was concluded that the improvement that had been achieved would warrant the performance evaluation and comparison.

In contrast to the designs of the Corporal-like injectors, the impingement point location and element orientation for an optimum injector design are not predetermined. However, if it can be assumed that a particular <u>mass distribution</u> can be specified then a procedure for defining the injector geometry may be summarized as follows:

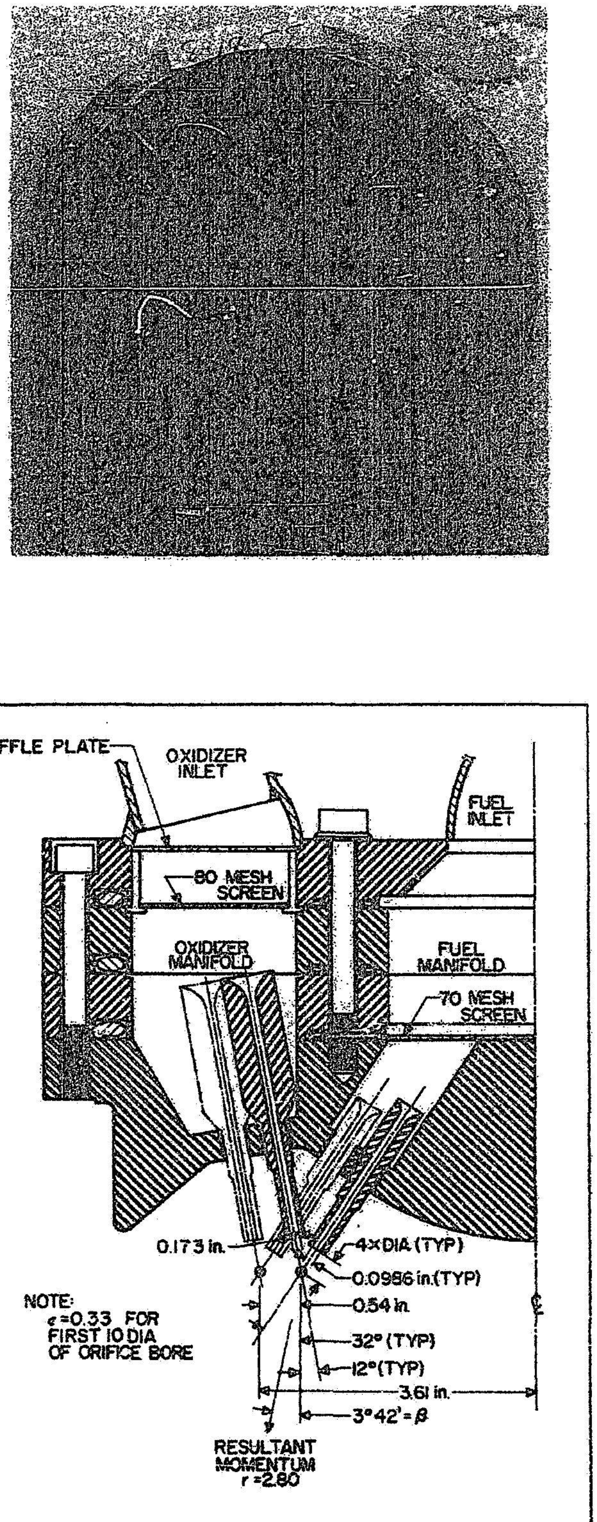


Fig. 4. Corporal-Like Injector No. 3(J-374) with Sketch of Orifice Geometry

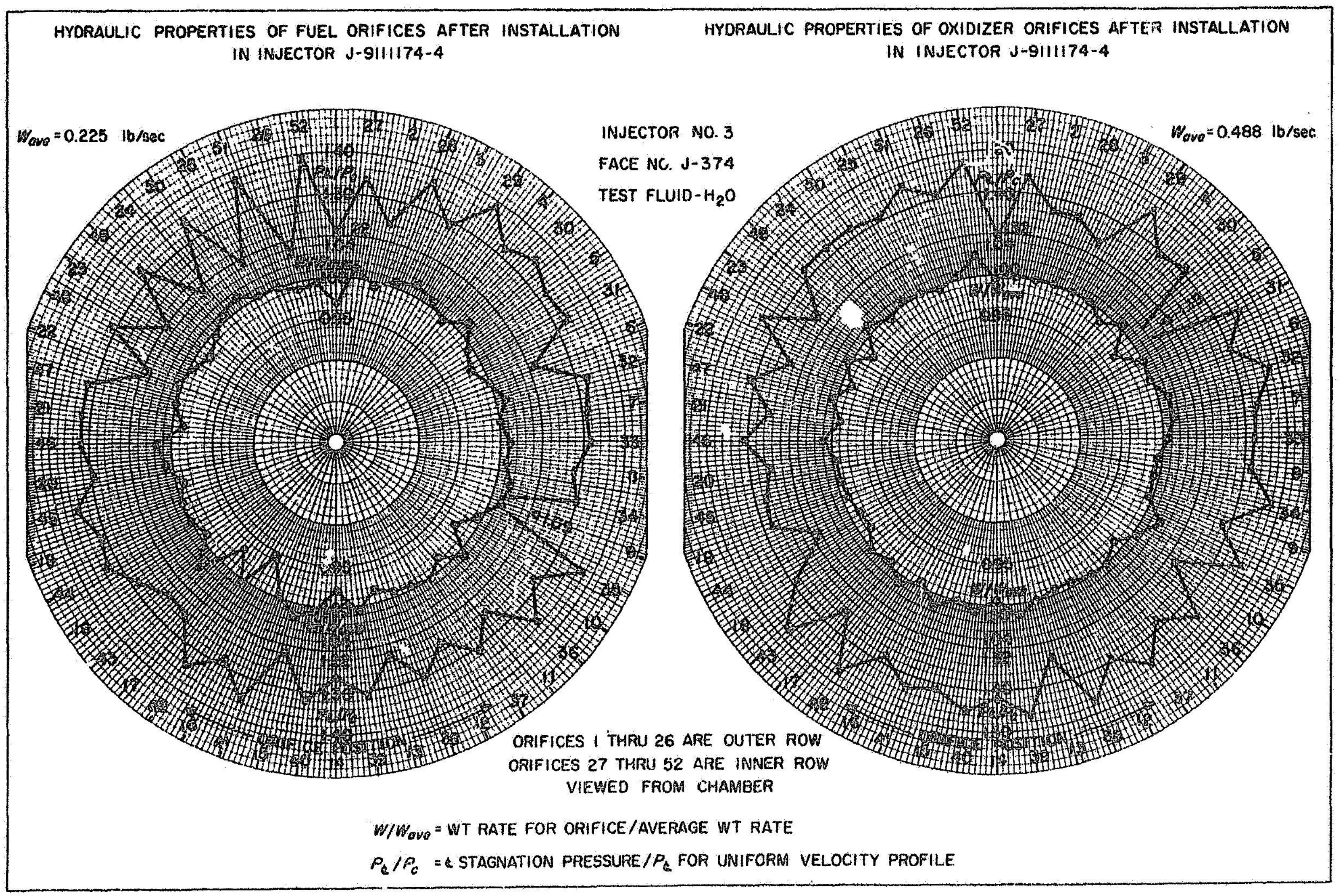


Fig. 5. Jet Properties of Corporal-Like Injector No. 3 (J-374)

1. Determine the mass distribution produced by the required element spraying non-reactive fluids. Use actual scale and propellant densities if possible.
2. Construct a three dimensional analogue of the element's axial-mass-flow rate from a photographic negative wherein density is analogous to mass-flow rate.
3. Prepare a composite model from the appropriate number of such negatives so as to produce the required distribution on a chamber section.
4. Utilize the orientation of (3) to define the required orifice and manifolding geometry.

This is the procedure that was followed in producing the final injector of the series which was intended to produce nearly uniform axial-mass-flow-rate distribution as well as uniform mixture-ratio distribution.

The mass distribution data were obtained with the carbon-tetrachloride - H_2O system, which nearly duplicates the physical properties of the acid-aniline system. The element had the same geometry as had been defined for Injectors 3 and 4 in order to retain similarity with the Corporal-like injectors, except for element location. This information was used to construct the analogue shown in Fig. 6 which illustrates the mass flow rate distribution obtained on a plane located six inches from the impingement point. It was obtained by setting the spray boundary at an iso-mass-rate line equal to 1.0% of the maximum and dividing the remaining range into 11 equal increments. Obviously, the mass distribution produced by this element is far from uniform, and further, has only one axis of symmetry. As will be seen, this latter effect can also influence element orientation.

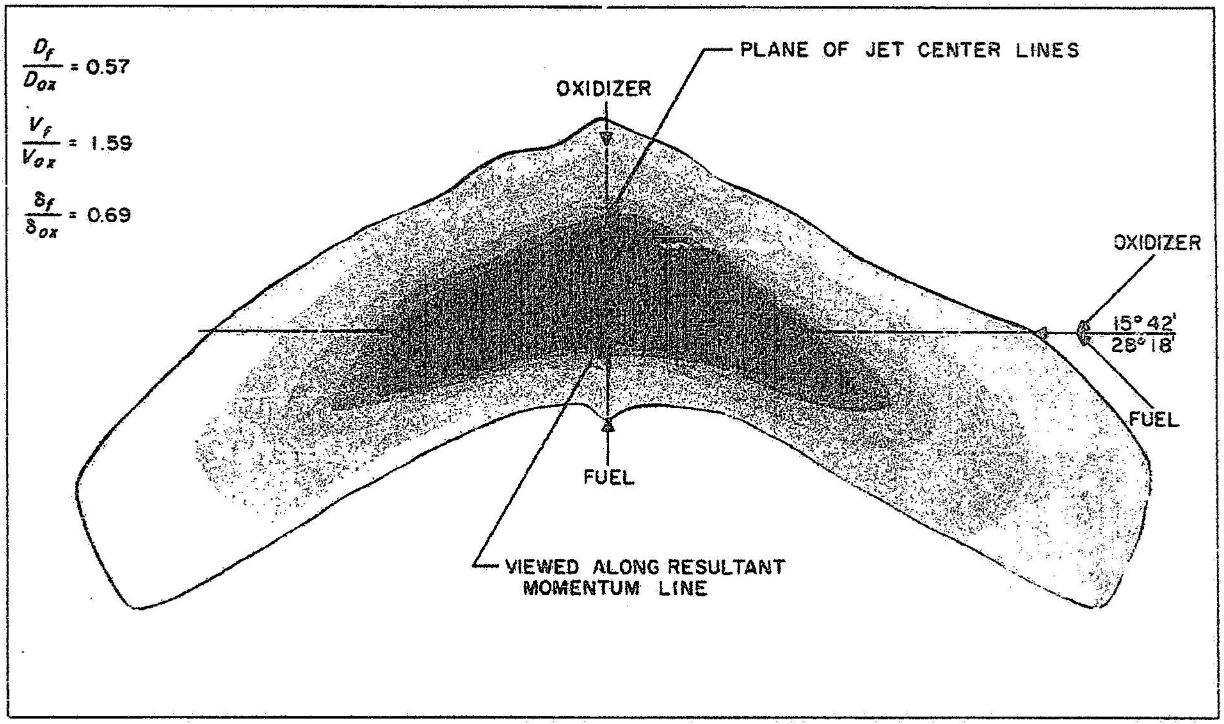


Fig. 6. Three-Dimensional Analogue of Mass Distribution Produced by a Pair of Impinging Streams

Noting that the plane dimensions of such an analogue are a function of the distance from the impingement point and, hence, that for a given element-flow rate the local values must also be proportional to the distance from the impingement point, introduces the necessity for establishing a "model plane" for which the composite distribution is to be evaluated. For the pruposes of this experiment, it was assumed that all spray particles emanated radially from the impingement point, and that the distance to the model plane would be sufficient to produce a spray cross-sectional area equal to an element's proportionate share of the chamber cross section. Once this distance (hence area) had been established, the mass-distribution analogue was scaled down an appropriate amount and 52 copies were obtained. These analogues were then used in conjunction with geometrical considerations to establish an arrangement that would produce a near uniform mass distribution. Actually, it was necessary to compromise a best possible arrangement somewhat, in order to resolve the fabrication problems. The final distribution pattern is shown in Fig. 7, where it can be seen that even though the elements tend to be arranged in rows, the fuel and oxidizer orifice positions are transposed in adjacent rows. For comparative purposes, a similar model based on the impingement point locations of the Corporal-like injectors is shown in Fig. 8.

The final injector design used a different orifice geometry than had been utilized for the Corporal-like injectors in order to achieve the required stream properties while eliminating the influences of the manifold. This was accomplished through the use of precision bore tubing in 100 L/D lengths for the orifices and equal-pressure-drop flex lines (a set per propellant) to join these orifices to the manifold. The physical result of this arrangement is shown in Fig. 9, which includes a view of the injector face as well as a view of the orifice-to-manifold assembly. Again, as with the Corporal-like injectors, the hydraulic properties of each jet were checked; but in this case it is sufficient to state that the flow rate variations were less than ±0.6% from the average and that the centerline-stagnation-pressure-ratio varied by less than ±0.5% and differed by less than 2% from the value that would be expected for fully developed turbulent flow at the orifice exit.

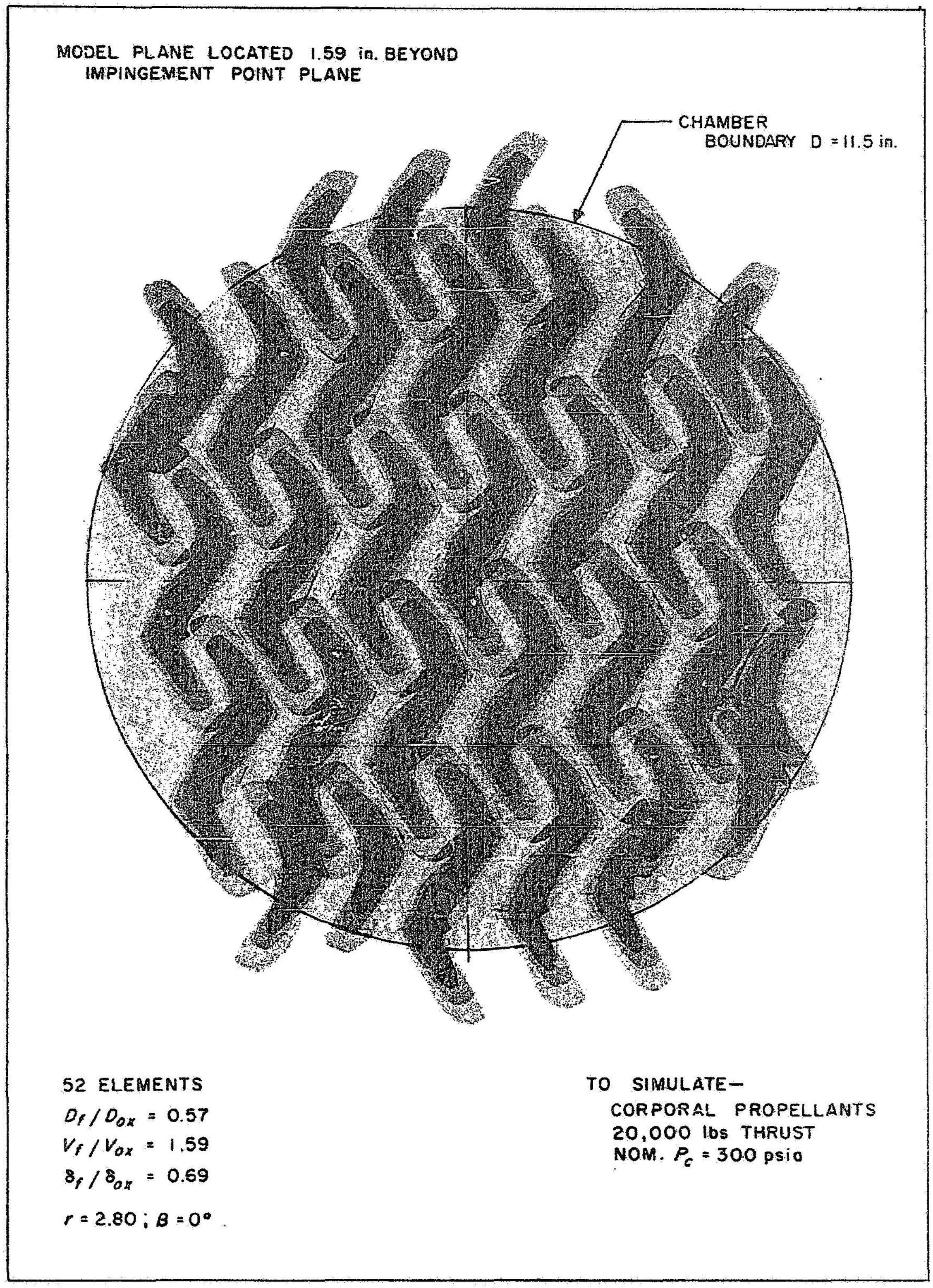


Fig. 7. Composite Model of Near-Uniform Distribution Obtained with a 52 Element Injector

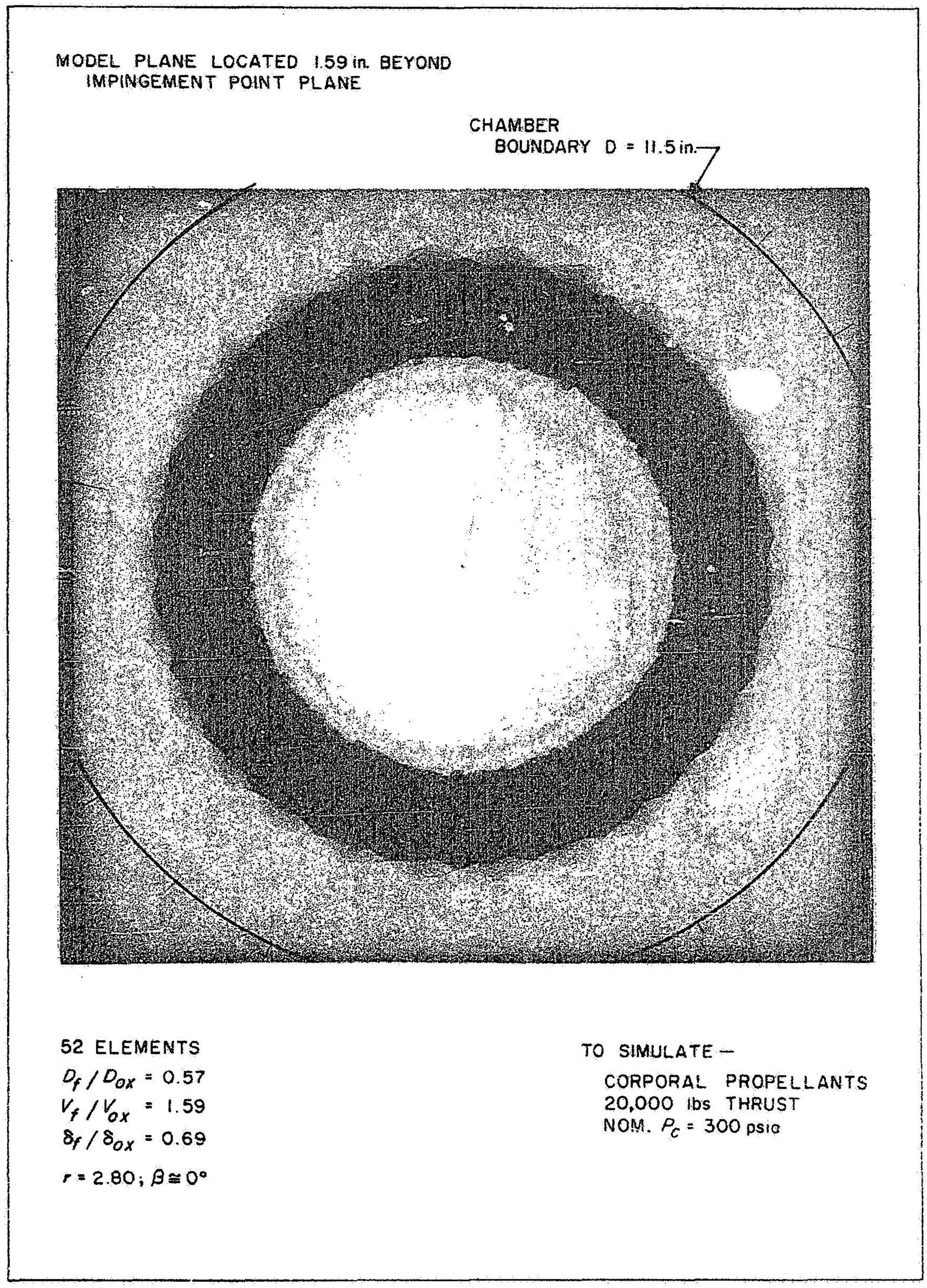


Fig. 8. Composite Model of Mass Distribution
Produced by a Corporal-Like Injector

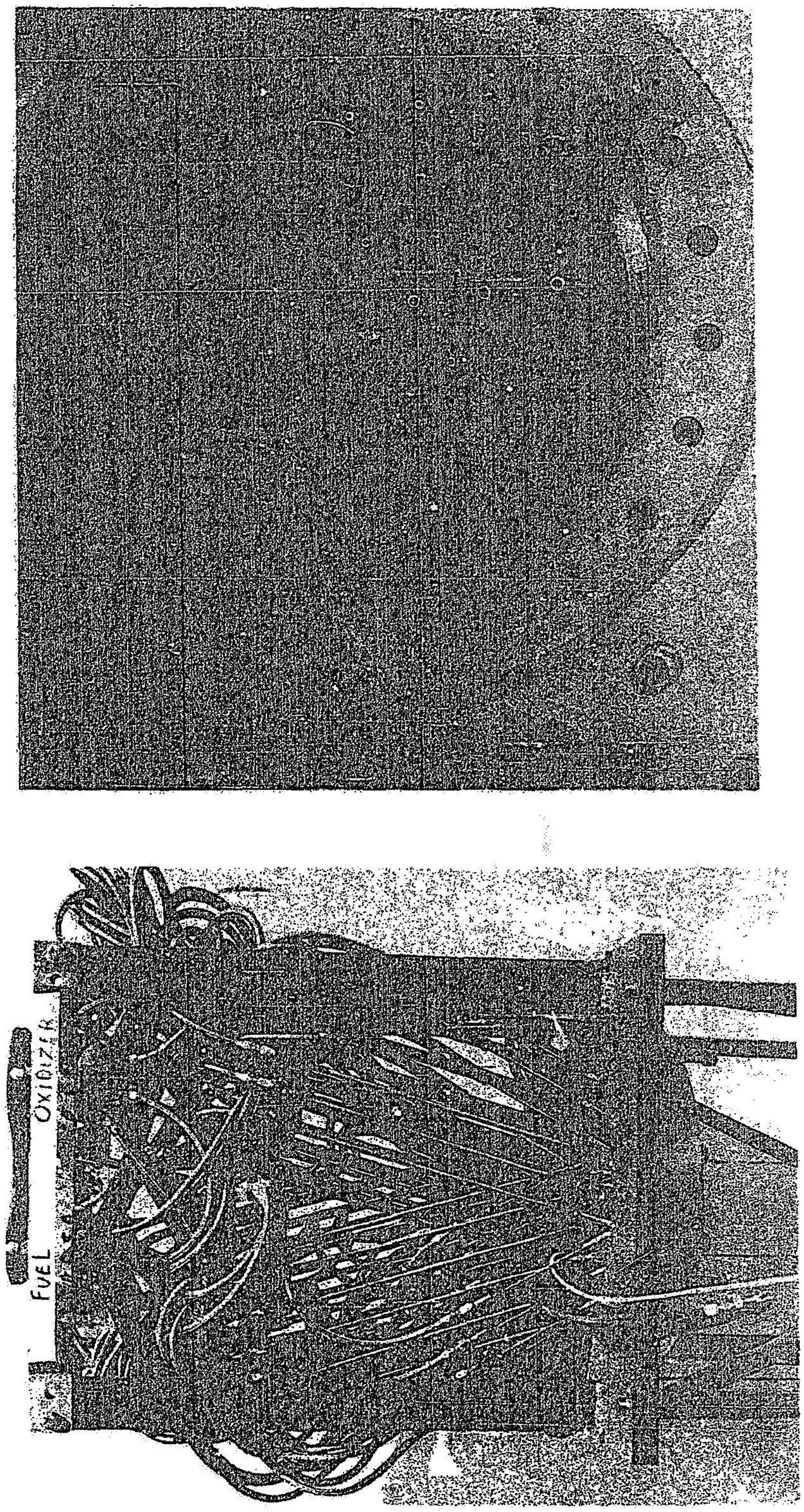


Fig. 9. Uniform Mass and Mixture-Ratio-Distribution Injector Utilizing 100 L/D Orifices

Although these data do represent an "improvement" in injector properties, these changes were assumed to have a negligible (at least quite small) effect on combustion processes. This was an obligatory assumption, in view of the absence of a quantitative relation between such differences and either spray properties or combustion, and because of the relative difficulty encountered in improving the properties of the Corporal-like injectors.

V. COMBUSTION PERFORMANCE EVALUATION

The performance of these several injectors were evaluated by comparing the over-all combustion properties of each injection scheme when adapted to otherwise similar, uncooled chambers and nozzles in a short-duration test stand located at the JPL facility at Edwards Air Force Base, California. Tests were nominally 2-3 seconds long and, in most cases, steady state conditions were achieved within 0.5-0.6 seconds. Engine performance was determined from experimental measurements of propellant flow rates, chamber pressures, thrust and several values of the local heat transfer rates in the chamber. At least one chamber pressure measurement had reasonably flat response to frequencies of 8-10 kc. These primary measurements (together with the usual supplementary information) were then used to compute an effective chamber pressure, P_{c-eff} C^*, I_{sp}, and the thrust coefficient, C_F. The effective chamber pressure was obtained by correcting the measured nozzle inlet pressure in accordance with the procedures of Ref. 7. C^*, I_{sp}, and C_F were obtained from the usual relationships $C^* = (P_{c-eff} \times f_t \times g)/\dot{W}$; $I_{sp} = F/\dot{W}$; and $C_F = F/P_{c-eff} \times g$. It is noted that somewhat lower values for $P_{c\,-\,eff}$ (in the order of 2-3%) are obtained if the injector-end chamber pressure is used for this calculation. However, the values based on nozzle inlet pressure produced thrust coefficients that were nearly equal to the expected values and, therefore, were considered more representative of the system.

Figures 10 through 12 compare the curves of C* and I_{sp} vs r for the six injectors that were included in the demonstration. Figure 10, in particular, clearly indicates the improvement in performance that was achieved by applying the results obtained with non-reactive fluid to an actual combustion chamber, and further, by assuming that both uniform mass distribution and uniform mixture-ratio distribution are required for optimizing the reaction. It is noted that the experimental C* is, essentially, a constant 98% of the theoretical equilibrium value, and that this represents an improvement of 13% over the Corporal system at peak performance mixture ratio.

It will also be noted that the performance for the Corporal injector has been plotted to illustrate the marked discontinuity that occurs at r = 2.24. This actually represents the inception of combustion instability characterized by a 140 cyc/sec oscillation with peak-to-peak amplitudes of at least 100 psi.

It should also be noted at this point that all of the injectors with the exception of the Corporal would produce a violent combustion instability, characterized by chamber pressure fluctuations of approximately 2-3000 psi at a frequency of approximately 1.8-2.0 kc. Even the heavy weight hardware that was used could not tolerate these conditions for more than 200-300 msec, so it was necessary to eliminate

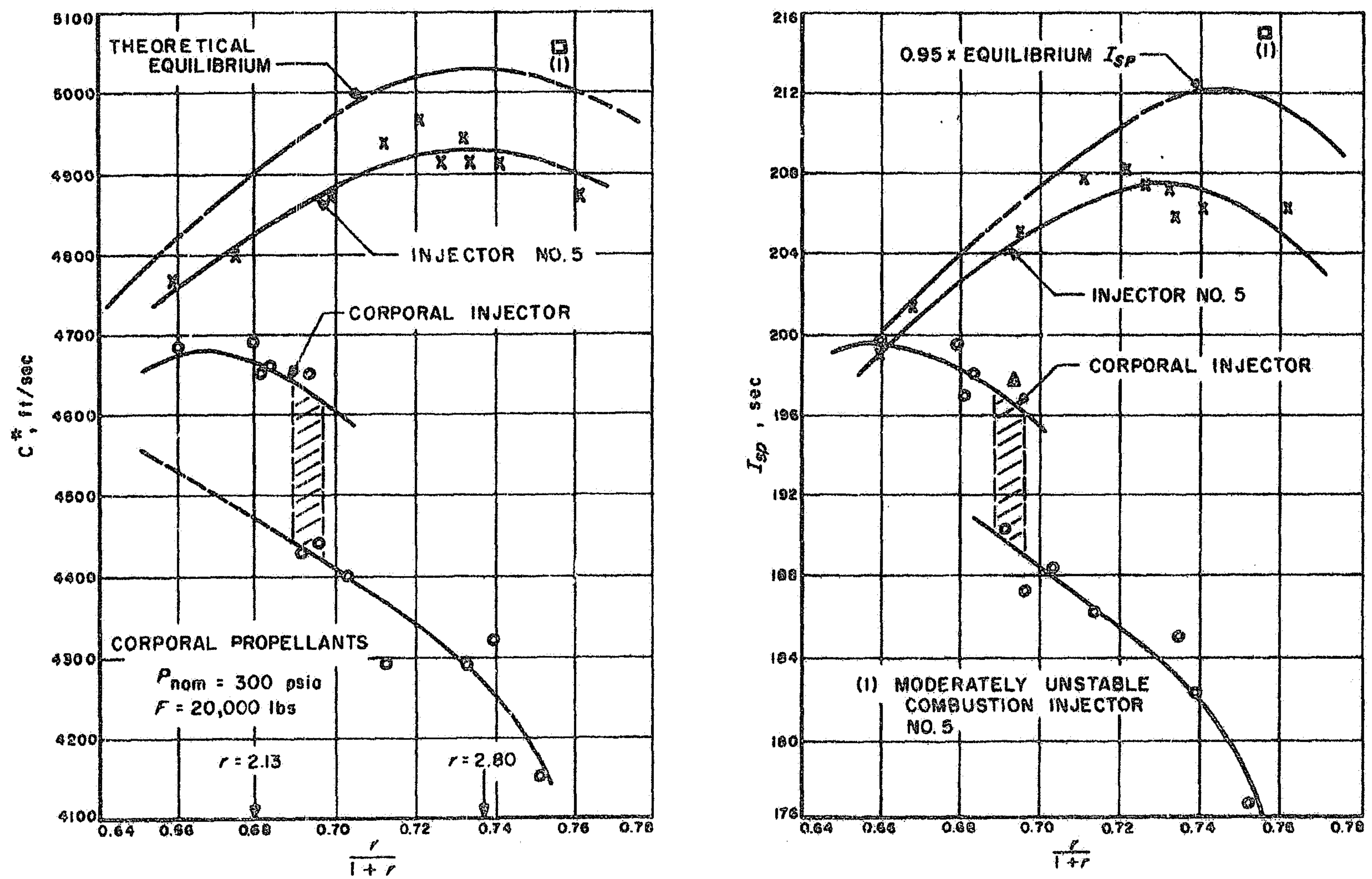


Fig. 10. A Comparison of the Experimental Performance of a Corporal Injector with Injector No. 5

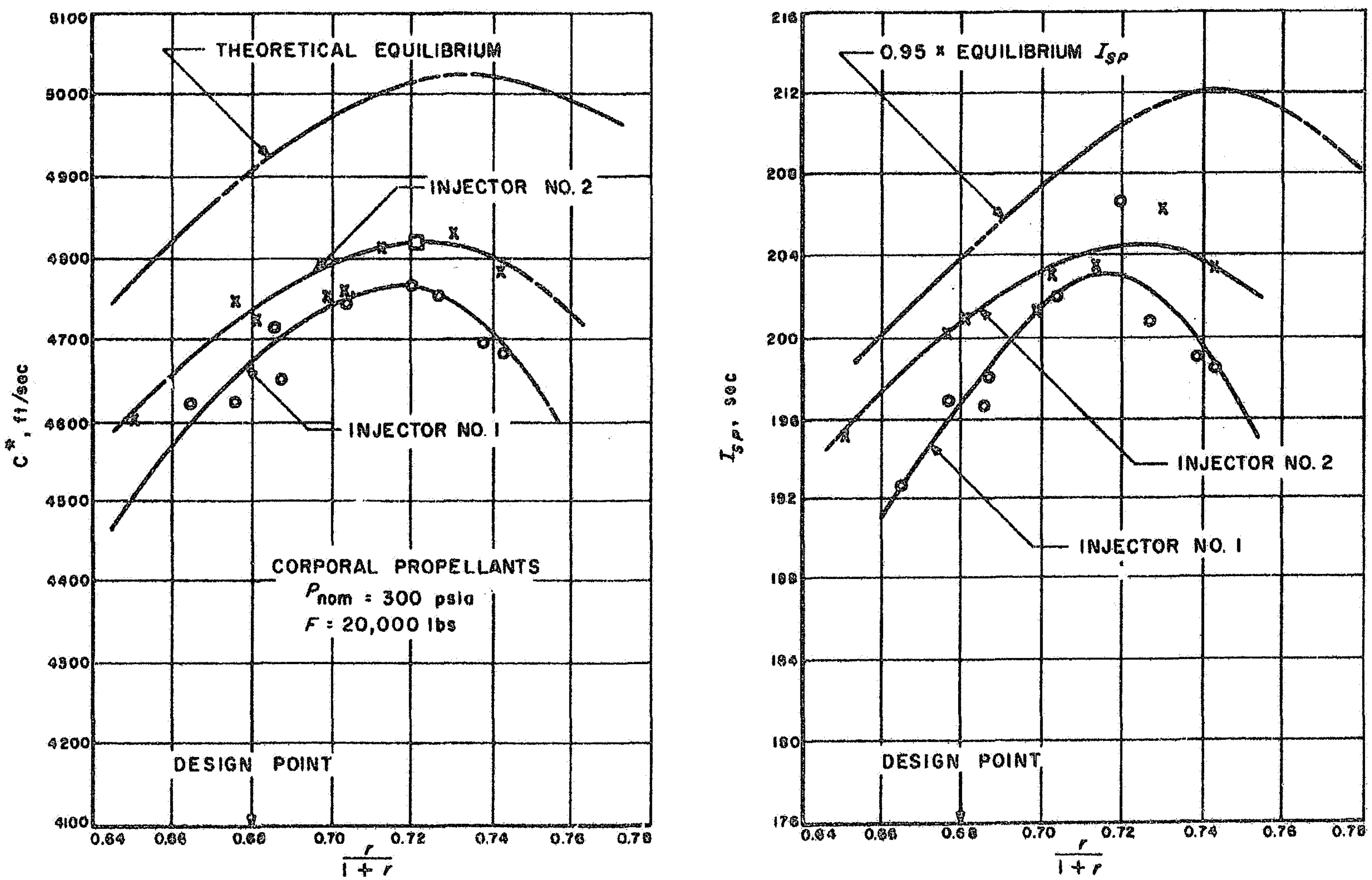


Fig. 11. The Experimental Performance of Two Corporal-Like Injectors Designed for Uniform r-Distribution at r = 2.13

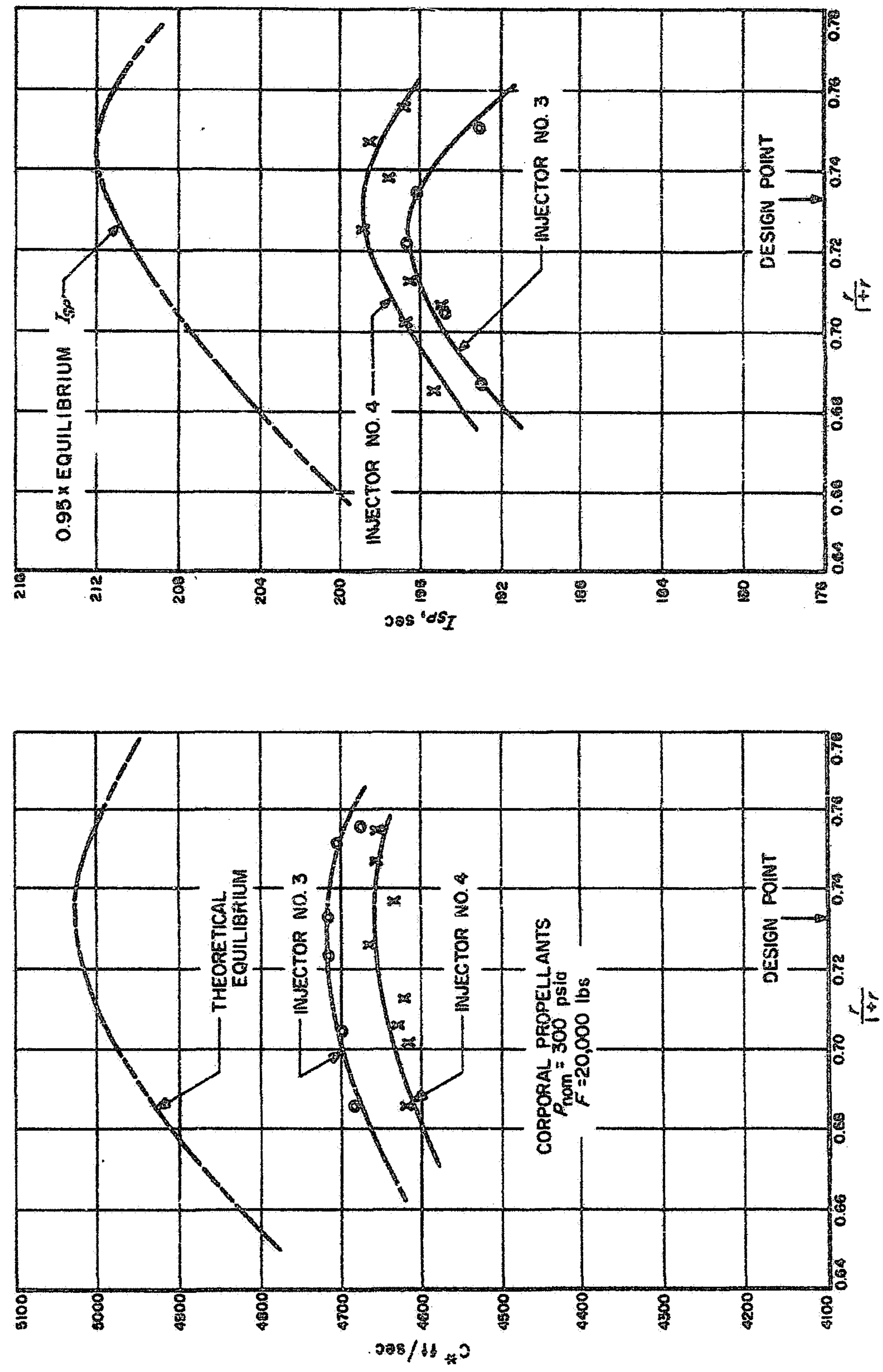


Fig. 12. The Experimental Performance of Two Corporal-Like Injectors Designed for Uniform r-Distribution at r = 2.80

this phenomena before any of these comparisons could be made. This was accomplished by installing a set of vanes, as shown in both Figs. 4 and 9, in a near-radial plane and extending 1.5-2.5 in. beyond the impingement point. No attempt was made to analyze the instability nor the damping mechanism that the vanes introduced. It was sufficient for the purposes of these experiments that the instability was eliminated, and, in a manner that did not appear to seriously modify either mass distributions or mixture-ratio distribution. Note that the vanes installed on the Corporal injector as shown in Fig. 3 had no measurable effect on the combustion characteristics produced by that injector.

Figure 11 shows the experimental performance of the two Corporal-like injectors that were designed to produce uniform mixture-ratio distribution at r = 2.13. It is interesting to note that, in this case, peak performance is obtained at a mixture-ratio value that is intermediate between the design r and peak-performance mixture ratio. Peak-performance for both injectors represents an improvement relative to the Corporal injector but, in neither case, does it approach the performance of injector 5 except at the low mixture ratios. It is also interesting to note that a small difference in performance (approximately 1%) can be associated with the changes in distribution, resulting from changes in resultant-momentum angle.

Figure 12 summarizes the experimental performance of the two Corporal-like injectors intended to produce uniform mixture-ratio distribution at r = 2.80. As should have been expected, the peak-performance mixture ratio for both of these injectors occurred very near the peak theoretical value. However, the fact that the absolute value is actually somewhat lower than the peak value (at a different r) obtained with injectors 1 and 2 was not expected. Nor is the small change in performance associated with the change in resultant momentum angle consistent with that obtained with 1 and 2. However, all of these differences are small enough so that it is difficult to attribute them to the effects of any one parameter. It does, however, seem quite clear that injectors 3 and 4 do achieve peak performance at or near peak-performance mixture ratio and, in addition, tend to be quite insensitive to changes in mixture ratio.

VI. SUMMARY

A summary of the performance characteristics is presented in Table 2 which compares the peak performance values for the several injectors against the peak theoretical values. It is to be noted that only injectors 3, 4, and 5 produced their peak performance at the design mixture ratio and in particular that injector 5 achieved a performance level that is significantly higher (i.e., 2 - 4% I_{sp} and 3 - 5% c*) than any of the other injectors.

Therefore, insofar as the information produced by a demonstration utilizing a single propellant system is concerned, it may be concluded that:

1. The non-reactive properties of sprays can be utilized to predict and control mass and mixture-ratio distributions in a combustion chamber.

2. The peak performance of a combustion chamber is achieved when the reactants are injected in a manner that will produce both uniform mixture-ratio distribution and uniform axial-mass-flow-rate distribution.

Table 2. Injector Performance Summary

Injector	Corporal	1	2	3	4	5
Mass Distribution	poor	poor	poor	poor	poor	good
r Distribution	poor	good	good	good	good	good
Design r	2.65	2.13	2.13	2.80	2.80	2.80
Peak Perf. r	2.13	2.56	2.66	2.80	2.80	2.80
Max $I_{sp}/Max(I_{sp})_{TH}$	0.895	0.908	0.916	0.880	0.890	0.927
Max $c^*/Max(c^*)_{TH}$	0.932	0.949	0.960	0.940	0.928	0.982

NOTE: Maximum $(I_{sp})_{TH}$ = 223.4 seconds; maximum $(c^*)_{TH}$ = 5020 ft/sec based on equilibrium values for r = 2.80.

NOMENCLATURE

E_m = mixing factor (see Ref. 3 for definition).

δ = weight density, lb/ft^3.

V = mean velocity, ft/sec.

D = diameter, in.

W = weight rate of flow, lb/sec.

r = mixture ratio = $W_{ox}/W_f = W_2/W_1$.

p = total stagnation pressure, psi.

p_c = centerline stagnation pressure producer with jet having a uniform velocity profile.

P_{c-eff} = isentropic stagnation pressure of combustion chamber, psia.

f_t = exhaust nozzle throat area.

g = gravitational constant.

F = thrust, lbs.

ϵ = nozzle expansion ratio or roughness factor.

β = angle between resultant momentum line and chamber axis at design r.

Subscripts

ox = oxidizer.

f = fuel.

1 = first component of system to simulate fuel.

2 = second component of system to simulate oxidizer.

T = total.

avg = average.

℄ = centerline

c = chamber.

NOMENCLATURE (Cont'd)

t = throat.

o = atmospheric or reference.

nom = nominal.

eff = effective.

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